A layered strategy for tackling antimicrobial resistance: the Swiss cheese model for policy, prevention, and engagement

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Murphy's Law, "anything that can go wrong will go wrong",[1] finds no more fitting application in public health than in the case of antimicrobial resistance (AMR). AMR will emerge whenever conditions permit. Despite robust evidence on the health and economic burdens of AMR, policy makers, governments, and international organisations face persistent challenges in implementing and financing comprehensive strategies.[2] Low political will, competing health priorities, weak health systems, and economic constraints hinder meaningful action.[3] Although few countries have made progress, such as the stringent antimicrobial stewardship programmes in Sweden[4] or the robust approaches of the Netherlands to reduce, monitor, and benchmark antimicrobial use in livestock,[5] the meagre number of effective policies only highlights the broader global inertia. Without sustained investment, strategic communication, and coordinated action, AMR will continue to threaten public health, undermine modern medicine, and impose substantial economic costs.[6]

Given these challenges, improved communication strategies are needed to raise awareness and policy change. The Swiss cheese model of system error, widely used to analyse adverse events in complex systems, provides a compelling framework for this purpose.[7] By illustrating how successive imperfect layers of defence can prevent harm when aligned effectively, the model communicates the importance of coordinated multilevel responses. Originally developed in the aviation sector[8] and subsequently adopted in health care,[9] the model gained prominence during the COVID-19 pandemic, when it helped communicate how layered interventions such as masking, distancing, and vaccination work synergistically to reduce transmission risk.[10]

Applying the Swiss cheese model to AMR highlights the necessity of multisectoral collaboration, coordination, communication, and capacity building (figure). We propose 15 codependent layers of contexts, strategies, and policies necessary to build a robust multitiered risk-reducing defence against AMR. These layers are grouped together within three categories, including One Health contexts, targeted interventions, and resource allocation.[12] The holes in the figure represent system failures that the resistant pathogens use to penetrate the various layers. When holes align, multiple system failures occur at once, with successful mitigation preventing complete system failure.

One Health contexts describe situations in which AMR emerges and disseminates across human, animal and plant, and environmental health. Within human health contexts, the behaviours of both the public and health-care providers influence the spread and emergence of AMR, including inappropriate use and prescription of antimicrobials[13] and poor applications of infection prevention and control (IPC) measures such as hand hygiene, driving transmission of resistant pathogens in communities, hospitals, and long-term care facilities.[14] Self-medication and misconceptions about the effectiveness of antimicrobials against viral infections promote misuse across many regions.[15] In animal and plant health, the indiscriminate use of medically important antimicrobials for prophylaxis and metaphylaxis as growth promoters in food-producing animals and spraying antimicrobials on fruit or rice as a prophylactic measure, for example, exacerbates AMR in the agri-food sector.[16] In environmental health contexts, pharmaceutical waste, agricultural runoff, and untreated wastewater contribute to environmental reservoirs of resistance in water systems, the atmosphere, manure-treated soils, and aquatic environments.[17] Resistant bacteria within these environmental reservoirs share resistance genes with other bacteria through horizontal gene transfer.

Target interventions describe nine strategies applicable across One Health contexts that need to be operating effectively to reinforce AMR containment. Sanitation refers to strengthened access to clean water, sanitation, and hygiene (WASH) in environments where humans and animals coexist. WASH reduces transmission of infections among potential hosts, reducing the need for antimicrobials and the subsequent selection pressure for the development or escalation of AMR.[18] Widespread vaccination in humans and animals reduces transmission of infection, thus lowering the demand for antimicrobials and, therefore, the selection pressure on pathogens.[19] Promoting IPC requires strengthening hospital waste management, disinfection and sterilisation, routine

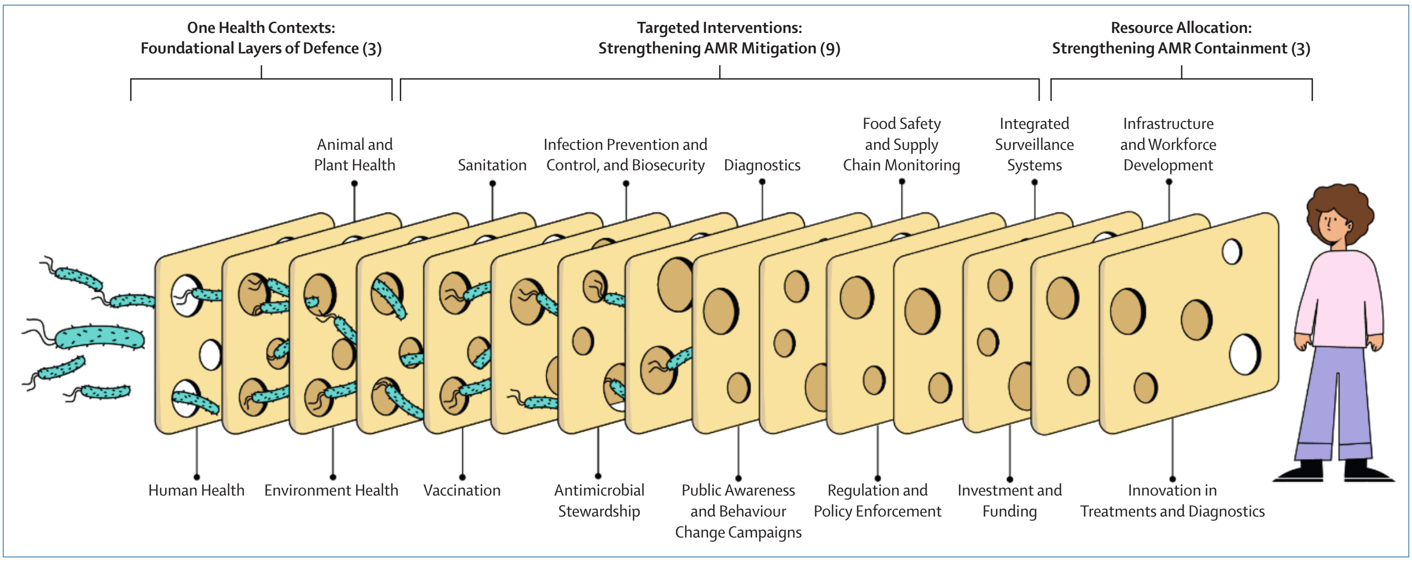

***Figure:* The antimicrobial resistance Swiss cheese model**
Adapted from Mackay (2020).[11] AMR=antimicrobial resistance.

screening for resistant pathogens, and enhancing biosecurity in agriculture.[20] Implementing stewardship programmes across human health-care, veterinary, and agricultural sectors ensures appropriate use of antimicrobials.[21] Strengthening diagnostics requires investments in microscopy, culture, and sensitivity, molecular tools, rapid diagnostics, and point-of-care testing of humans and animals to improve treatment precision by enabling targeted antimicrobial therapy and reducing unnecessary use of antimicrobials.[22] Public awareness and behaviour change campaigns need to educate the public on the dangers of AMR, risks of self-medication, and importance of completing antimicrobial courses to foster responsible antimicrobial use.[23] Behaviour change techniques, such as peer comparisons and benchmarking,[24] can be used to reduce inappropriate use of antimicrobials by professionals involved in the human health and agri-food sectors. Food safety and supply chain monitoring involves strict food safety regulations, improved hygiene in meat processing, and antimicrobial-free supply chains to help to reduce the risk of food-borne AMR.[25] Regulation and policy enforcement incorporating these regulatory frameworks should apply penalties for non-compliance and incentives for responsible use of antimicrobials. IPC programmes and biosecurity measures are needed to enhance accountability and implementation of the recommended policies.[26] Integrated surveillance systems should track resistance within and across humans, animals, plants, and the environment to provide crucial data for early detection and targeted interventions.[27]

Resource allocation involves increased investment and funding, workforce and infrastructure development, and innovation in novel treatment and diagnostics. Strengthening investment and funding will require governments and multilateral organisations to allocate appropriate and sustained funding for AMR research, education, and implementation strategies, ensuring equitable access to interventions worldwide. This approach requires costing activities outlined within AMR national action plans to enable a balanced mix of global and domestic financing streams. Infrastructure and workforce development involves expanding laboratory capacity for quality-assured representative surveillance.[28] Key priorities include increasing workforce capacity to implement surveillance, IPC, biosecurity measures, and stewardship programmes and enhancing medical and veterinary education. Innovation in novel treatments and diagnostics needs investment in incentives for novel antimicrobials, alternative therapies, and improved diagnostics to optimise treatment and prevention strategies.[29] Global collaboration through platforms such as the G7 and G20 and organisations, such as the WHO, World Organisation for Animal Health (WOAH), Food and Agriculture Organization of the UN (FAO), and United Nations Environment Programme (UNEP), is key for harmonising investment prioritisation criteria and ensuring equitable access to new treatments.

The Swiss cheese model offers a powerful communication tool for conveying the complexity of AMR and the imperative for a coordinated multilayered response. By visually representing how actions across the One Health contexts, targeted interventions, and resource allocation interact and complement one another to drive and mitigate AMR, this model enhances the understanding among policy makers, health-care professionals, veterinarians, environmental agencies, and the public. The model also underscores the urgency of a coordinated sustained response to prevent resistance from undermining modern human and veterinary medicine. With collective commitment and strategic investment, the global community can preserve the effectiveness of antimicrobials for future generations.

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